WESTINGHOUSE'S ADVANCED TURBINE SYSTEMS PROGRAM

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ABSTRACT

The paper describes the goals of the Westinghouse Advanced Turbine Systems program. This program is being undertaken in response to the DOE Fossil Energy requirements for improved efficiency, lower cost of electricity, lower emissions, and state-of-the-art reliability levels.

It describes in detail the objectives of the program and the approach taken by Westinghouse to achieve those goals. The evolutionary approach taken by Westinghouse is explained together with the development program and component testing undertaken in the last year.

The benefits of this new advanced turbine are discussed and the future activities of the program are explained.

INTRODUCTION

U.S. Department of Energy, Office of Fossil Energy Advanced Turbine Systems Program is a multi-year effort to develop the necessary technologies, which will result in a significant increase in natural gas-fired power generation plant efficiency, a decrease in cost of electricity and a decrease in harmful emissions. In Phase 1 of the ATS Program, preliminary investigations on different gas turbine cycles demonstrated that net plant efficiency greater than 60% is achievable. The more promising cycles were evaluated in greater detail in Phase 2 and the closed-loop cooled combined cycle was selected because it offered the best solution with the least risk for achieving the ATS Program goals of net plant efficiency, emissions, cost of electricity, reliability-availability-maintainability (RAM), as well as commercial operation by the year 2000.

The Westinghouse ATS plant is based on an enhanced technology gas turbine design combined with an advanced steam turbine and a high efficiency generator. To meet the challenging performance, emissions, and RAM goals, existing technologies were extended and new technologies developed. The attainment of ATS performance goal necessitated advancements in aerodynamics, sealing, cooling, coatings, and materials technologies. To reduce emissions to the required levels, demanded a development effort in the following combustion technology areas: lean premixed ultra-low NOx combustion, catalytic combustion, combustion instabilities, and optical diagnostics. To achieve the RAM targets, required the utilization of proven design features, with quantified risk analysis, and advanced materials, coatings, and cooling technologies.

The 501ATS engine is the next frame in the series of successful utility turbines developed by Westinghouse over the last 50 years. During that time, Westinghouse engineers made significant contributions in advancing gas turbine technology as applied to heavy-duty industrial and utility engines. Some of the innovations included single-shaft two-bearing engine design, cold-end drive, axial exhaust, first cooled turbine airfoils in an industrial engine, and tilting pad bearings, features which all major gas turbine manufacturers have incorporated in their designs. The evolution of large gas turbines started at Westinghouse with the introduction of the 45 MW 501A engine in 1968 (see Table 1). Continuous enhancements in performance were made up to the 100 MW 501D5 introduced in 1981. The next engine was the 160 MW 501F introduced in 1991. The 230 MW 501G was next in the series and is the initial step in ATS engine development. Each successive engine design was based on the proven concepts used in the previous design.

The 501F was introduced at 160 MW and a simple cycle efficiency of 36%. Its current uprated rating is 167 MW and its combined cycle net efficiency is greater than 55%. The first four 501F engines that entered service with Florida Power and Light have demonstrated 99% reliability and 94% availability in over 33,000 operating hours each.

The 501G produces 230 MW in simple cycle and its combined cycle net efficiency is 58%. This engine incorporates further advancements in materials, cooling technology, and component aerodynamic design. The 19:1 pressure ratio compressor uses advanced profile high efficiency airfoils. The combustion system incorporates 16 dry low NOx combustors, with similar flame temperature as in the 501F, and hence, the same low emissions. This was made possible by the closed-loop steam cooled transition design, which eliminated transition cooling air ejection into the gas path. The four-stage 501G turbine uses full 3-D design airfoils and proven aeroderivative materials and coatings.

Westinghouse's strategy to achieve, and exceed, the ATS Program goals is to build on the proven technologies used in the successfully operating fleet of its utility gas turbines, such as the 501F, and to extend the technologies developed for the 501G.

ATS DESCRIPTION

The ATS plant consists of the gas turbine, generator, and steam turbine, connected together in an in-line arrangement with a clutch located between the generator and the steam turbine. The gas turbine exhaust gases produce steam in the three-pressure level heat recovery steam generator. The high pressure steam turbine exhaust steam is used to cool the transitions and two rows of stators. The reheated steam is then returned to the steam cycle for induction into the intermediate pressure steam turbine.

The ATS engine is a state-of-the-art 300 MW class design incorporating many proven design features used in previous Westinghouse gas turbines and new design features and technologies required to achieve the ATS Program goals.

Compressor

The compressor shares many common parts with the 501G 16-stage compressor. The mass flow is identical, but the ATS higher rotor inlet temperature and closed-loop cooling has required an increase in pressure ratio from 19:1 to 29:1. This increased pressure ratio was achieved by adding stages to the rear of the 501G compressor. The latest 3-D viscous codes and custom-designed airfoils were used in the compressor aerodynamic design. Variable stators have been added to stages 1 and 2 to improve starting capability and part-load performance.

Combustion System

The 501ATS incorporates 16 combustors based on the lean premixed multi-stage piloted ring design. The burner outlet temperature was kept at the same level as in the 501F and 501G, by using closed-loop steam cooling (with air as an alternate coolant) in the transitions and turbine stators, so that more compressor delivery air was available in the combustor head end. Therefore, this allowed very lean, premixed combustion and hence single digit NOx emissions.

To aid in ATS combustor design and development, extensive use was made of computational fluid dynamics (CFD) analysis. Using CFD analysis expedited combustion system development and allowed screening of modifications prior to testing. This resulted in combustors with more predictable performance and reliability.

Turbine

The four-stage turbine design was based on 3-D design philosophy and viscous analysis codes. The airfoil loadings were optimized to enhance aerodynamic performance while minimizing airfoil solidity. The reduced solidity resulted in lower cooling requirements and increased efficiency. To further enhance plant efficiency, the following features were included: turbine airfoil closed-loop cooling, active blade tip clearance control on the first two stages, improved rotor sealing, and optimum circumferential alignment of airfoils.

The ATS engine utilized advanced thin wall designs with thermal barrier coatings and the state-of-the-art aero engine cooling technology. The first and second stage vanes used closed-loop steam cooling and the first two stages of blades used closed-loop air cooling. Air was chosen for blade cooling because it does not have the risks of steam corrosion, deposition, and complexity that closed-loop cooling with steam poses. In addition, the air can be cooled after it is removed from the combustor shell so that only relatively small amounts of cooling air are needed for the rotor. The cooling air is filtered to remove dirt particles before being ducted to the rotor blades. The difference in plant thermal efficiency between blade closed-loop cooling by air instead of steam is about 0.2%. Thus, based on a cost benefit analysis and RAM analysis, closed-loop air cooling is the preferred approach.

Westinghouse has been using thermal barrier coatings (TBC) on turbine airfoils since 1986 and has built an extensive experience base. It is a standard "bill of material" for new 501D5, 501F, and 251B11/12 engines. Recent field trials have demonstrated excellent results after operation for 24,000 hours. In the 501ATS engine, further improvements in TBC coating, with improved bond coats and new ceramic materials, will be utilized.

The 501ATS turbine design used the latest aero engine blade and vane nickel-based alloys. Single crystal nickel alloy, CMSX-4, was employed on the first stage vanes and blades to provide increased creep strength and fatigue resistance compared to conventional materials.

Rotor Design

The power level transmitted through the rotor and the resulting high stresses make rotor design an extremely important component of the engine. The 501ATS rotor consists of four ruggedized alloy steel discs clamped together with 12 through-bolts. Alloy steel was used to extend the excellent past operating experience with this material to the ATS engine and to reduce engine cost. In this design, torque transmission and alignment are achieved by the use of a Curvic™ clutch, which is a beveled male and female tooth form. This design has been proven by use on all Westinghouse-designed gas turbines over the past 40 years.

During the rotor design process, extensive finite element analysis modeling was carried out to calculate rotor critical speeds and cyclic life. In order to ensure rotor stability, a transient analysis from startup to baseload was carried out to verify that there was no slipping or gapping of the torque carrying members. The analysis has demonstrated that during all conditions analyzed, the torque carrying Curvic™ clutch arms do not come out of engagement. This virtually eliminates frettage or slippage which could give rise to vibration or cracking.

The compressor rotor is a series of discs clamped together with 12 through-bolts. However, the torque transmission is via friction and radial keys between all discs. This method was also used on the 501F and shown to be reliable. Alignment of the discs is maintained by a spigot at the base of the discs and by the shoulder on the radial pins. Computer modeling was used to ensure the rotor stability over its complete operating range with no chance of slippage or gapping.

TECHNOLOGY VERIFICATION PROGRAMS

To ensure that ATS program goals are achieved, an extensive technology verification program is in progress in the following areas: combustion, cooling, aerodynamics, leakage control, coatings, and materials.

Combustion

The 501ATS piloted ring combustor is the most successful candidate of combustors developed by Westinghouse over the past 10 years. It consists of a pilot and two separate premixed zones arranged axially, the primary and secondary zones. Premixed fuel and air enter the primary zone where combustion is stabilized by a swirl-produced recirculation zone and a centrally located pilot. The second zone is located downstream and is fed premixed fuel and air through an annular passage surrounding the primary zone. This combustor, which achieved single digit NOx emissions and excellent stability on low pressure tests, is currently undergoing evaluation at high pressures.

Cooling

Elimination of cooling air injection into the turbine flow path, as a result of closed-loop steam cooling, is the major contributor to the increase in ATS plant efficiency. This results in an increase in gas temperature downstream of the first stage vane and hence an increase in gas energy level during the expansion process. A secondary contributor is the elimination of mixing losses associated with cooling air ejection. The combination of these effects results in a significant increase in ATS plant efficiency. In addition, NOx emissions are reduced because more air is available for the lean premixed combustor at the same burner outlet temperature. Achieving acceptable blade metal temperatures in a closed-loop cooling design is a challenge due to the absence of a cooling air film to shield the turbine airfoil and shroud wall, and no shower-head or trailing edge ejection to provide enhanced cooling in the critical leading and trailing edge regions. To produce an optimized closed-loop cooling design, the following approaches were utilized: (1) airfoil aerodynamic design tailored to provide minimum gas side heat transfer coefficients, (2) minimum coolant inlet temperature, (3) thermal barrier coating applied on airfoil and end wall surfaces to reduce heat input, (4) maximized cold side surface area, (5) turbulators to enhance cold side heat transfer coefficients, and (6) minimum outside wall thicknesses to reduce wall temperature gradients and hence the internal heat transfer coefficients required to cool the airfoil.

The thin-wall closed-loop cooled first stage vane and blade design was completed and casting development started at Allison-Single Crystal Operations. To verify the critical cooling designs, a three part program was undertaken. The internal heat transfer coefficients and pressure drops are being measured on plastic models of the different vane and blade cooling features at Carnegie Mellon University. A liquid crystal thermochromic paint technique was used to measure the internal heat transfer coefficients. The outside heat transfer coefficients will be measured on model turbine tests. The first stage vane cooling design will be verified at ATS operating conditions in a hot cascade test rig in the Westinghouse high pressure combustion test facility located at the Arnold Engineering Development Center, in Arnold AFB, Tennessee.

Compressor Aerodynamics Development

To determine its performance and operating characteristics over the complete operating range, the full-scale ATS compressor was tested in a specially designed facility located at the

U.S. Navy Base in Philadelphia. The facility was designed for subatmospheric inlet pressure to reduce the power required to drive the compressor. The inlet system consisted of a filter house, straight pipe with a flow straightener and a flow meter, inlet throttle valve, diffuser with flow straightening devices, 90° bend with turning vanes, and a silencer. Because of the subatmoshperic operation, two stages of compressor bleed air were ducted into the inlet diffuser, after passing through coolers. The exhaust system included a large diameter back pressure valve to provide control on the test pressure ratio. A small diameter quick-acting valve, located in a bypass line around the large back pressure valve, was used for recovery from compressor surge.

The compressor was instrumented with static pressure taps, fixed temperature and pressure rakes, thermocouples, tip clearance probes, blade vibration monitoring probes, rotor vibration probes, acoustic probes, and strain gauges. Provisions were made for radial traverses in eight axial locations in the compressor and four radial locations in the inlet duct. More than 500 individual measurements were recorded. A dedicated data acquisition system was used to collect and reduce the test data. Important performance and health monitoring parameters were displayed on computer screens in real time. After the compressor test facility was commissioned, an extensive test program was performed. The test program included design point performance verification, blade vibration and diaphragm strain gauge measurements, inlet guide vane and variable stator optimization, compressor map definition and starting characteristics optimization.

Turbine Aerodynamic Development

The first two 501ATS turbine stages will be tested at 1/3-scale in a model turbine test rig, located at Ohio State University, to verify aerodynamic performance with reduced airfoil solidity, to quantify performance benefits due to optimum circumferential alignment of turbine airfoils, and to measure outside heat transfer coefficients on the airfoils of this advanced 3-D aero design turbine. The model turbine component manufacture was completed. Pressure sensor and thermocouple installation on the model turbine airfoils was also completed. The heat flux gauge installation is nearing completion. The test facility, which was moved from Buffalo to Ohio State University, was commissioned and is ready for model turbine testing.

Leakage Control

To reduce air leakage, as well as hot gas ingestion into turbine disc cavities, brush seals were incorporated under the compressor diaphragms, turbine disc front, turbine rim, and turbine interstage locations. A development program was initiated to incorporate an effective, reliable, and long-lasting brush seal system into a heavy-duty industrial gas turbine. Tests were performed to select the appropriate bristle materials, to quantify wear characteristics and to determine leakage. The brush seal performance under the compressor diaphragms was verified during the 501ATS compressor testing. To test their performance over long operating times, turbine interstage seals were installed on a new 501F engine and will be retrofitted into 501D5 engines.

A face seal was designed to prevent rotor cooling air leakage as it is introduced at the rotor rear. Seal hardware has been ordered and a test rig is being constructed. Tests will be carried out to verify the face seal performance.

Coatings

The ATS engine turbine component coatings must be capable of operation for 24,000 hours. To ensure this, a program is in progress to develop an improved bond coat/TBC system. Different bond coats are being evaluated under accelerated oxidation test conditions. New ceramic candidate materials are also undergoing testing. The objective of this program is to combine the optimum bond coat with the best performing TBC to provide a coating system with maximum service life at the ATS operating conditions. An advanced bond coat/TBC system has accumulated more than 20,000 hours in cyclic testing at 1010°C (1850°F) with excellent results.

Materials

To enhance performance and reliability, single crystal (SC) blades are used in the ATS engine. A casting development program was carried out to demonstrate castability of large industrial turbine blades in CMSX-4 material. Existing 501F engine tooling was used to cast single crystal blades. The castings were evaluated by grain etching, selected NDE methods and dimensional inspection methods to determine their metallurgical acceptability. After several trials, excellent results were obtained on a solid and a cored blade thus demonstrating that SC blades are castable in CMSX-4 alloy. Further process development is in progress to optimize post-cast heat treatment, evaluate effects of grain defects, generate SC material design data, and further develop the casting process.

FUTURE ACTIVITIES

Technology development efforts to date have demonstrated that ATS Program goals are obtainable. The results have been incorporated into the 501ATS design. Future ATS Phase 3 activities will complete the technology verification process. High pressure testing on the ATS piloted ring combustor will be carried out to optimize the design and demonstrate single digit NOx emissions. Catalytic combustion development will proceed toward full-scale testing of catalytic combustor by the end of the year. The two-stage model turbine tests, to verify aerodynamic performance and to measure outside heat transfer coefficients, will be completed. Rig testing will be completed on the turbine brush seals and rotor face seal. Abradability tests will be carried out on the turbine blade tip treatments, which will be applied to blade tips for wear protection. Pre-production casting development will continue on the single crystal thin wall stage 1 vanes and blades and thick wall stage 2 blades. Long term verification tests on advanced bond coat/TBC system will be carried out on test rigs and rainbow tests with coated blades on operating engines. The next phase of the ATS Program includes building the prototype 501ATS engine and carrying out extensive testing to verify its performance and mechanical integrity.

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Engine	501A	501B	501D	501D5	501D5A	501F	501G	501/ATS
Commercial Operation	1968	1973	1976	1982	1994	1993	1997	2000
Power, MW	45	80	95	107	120	160	230	420*
Rotor Inlet Temp.,°F	1615	1819	2005	2070	2150	2330	2583	2750
Air Flow, Lb/Sec	548	746	781	790	832	961	1200	1200
Pressure Ratio	7:5	11:2	12:6	14:1	15:1	15:1	19:1	29:1
No. Comp. Stages	17	17	19	19	19	16	16	20
No. Turbine Stages	4	4	4	4	4	4	4	4
No. Cooled Rows	1	3	4	4	4	6	6	6
Exhaust Temp., °F	885	907	956	981	1004	1083	1100	1100
Heat Rate (Btu/kWh)								
Simple	12,600	11,600	10,925	10,040	9,900	9,610	8,860	--
Combined	9,000	7,350	7,280	7,055	7,024	6,429	5,881	5,686

*Combined cycle output power